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DETECTABILITY OF KNOWN CRACKS UNDER FASTENERS USING ULTRASONIC IMAGING

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Executive Summary

The detection of fatigue cracks in fastener holes in aircraft structures has been an area of concern for many years. There has been considerable research devoted to improving nondestructive inspection techniques in order to reduce the minimum detectable crack size, and in particular, detecting cracks under installed fasteners. This paper describes results obtained using one of these. An ultrasonic shear wave technique was used to systematically inspect countersunk fastener holes in aluminum plates with a variety of simulated fatigue cracks of known dimensions at one of three known locations (countersink, mid-bore or faying surface). In addition to unflawed specimens, a total of thirty coupons, ten with each type of flaw, was studied.

Briefly, in this study the test specimens were mounted so that the known crack plane was oriented normal to the transducer axis. A 70° angle of incidence ultrasonic shear wave was used and the resulting reflections from the flaws were measured. All data were acquired using commercially-available, immersion C-scan instrumentation and a highly-focussed 25 MHz transducer.

After preliminary experimentation, a set of instrument settings was selected and each of the three holes in each of the coupons in the set was scanned under these fixed conditions. Scans were conducted on most of the holes when fasteners were removed as well as with ferrous and titanium fasteners installed. The effect of changing the transducer/crack plane orientation was also examined. Experiments in which all three holes in a coupon were scanned simultaneously were also performed, both with and without fasteners. Representative ultrasonic images produced are shown in Figures 2-12 and Table 1 contains a summary of all the results obtained in this study.

It was concluded that the ultrasonic shear wave technique was readily able to detect a variety of fatigue cracks in countersunk fastener holes both with and without fasteners installed. Although the insertion of ferrous or titanium fasteners changed some features of the ultrasonic images obtained, their presence or absence did not adversely affect the detectabilty of the flaws.
The smallest crack detected was 0.006", although most cracks were greater than 0.010" and some crack dimensions were as large as 0.25".

Although this study demonstrated that this technique is effective in detecting the presence of relatively small cracks under installed fasteners, it is not directly applicable to field use. It is an immersion technique, making it unsuitable for on-aircraft applications. The process also requires 15-20 minutes per scan, making it impractical for inspecting large numbers of holes. It is possible, however, that current on-aircraft scanning capabilities could be modified in order to perform this technique.

Detectability of Known Cracks Under Fasteners Using Ultrasonic Imaging

Introduction

The detection of fatigue cracks in fastener holes in aircraft structures has been an area of concern for many years. These cracks commonly initiate at the bottom of the countersink, but may be found at the faying surface or at the mid-bore of the hole. Their early and reliable detection is important. There has been considerable research devoted to increasing the sensitivity of nondestructive inspection techniques in order to reduce the minimum detectable crack size, and in particular, detecting those ocurring under installed fasteners.

This paper describes results obtained using one of these methods, an ultrasonic shear wave technique, to systematically inspect aluminum coupons with a variety of simulated fatigue cracks of known dimensions located at each of the three possible sites. These test specimens were manufactured by the Canadian Forces' Quality Engineering Test Establishment (QETE) as part of an international probability of detection (POD) study. They reproduce the geometry of the CF116 upper wing skin golden triangle area and are described in greater detail below (1). Details of the ultrasonic technique are also described elsewhere (2).

Test Specimens

Three 0.258" diameter countersunk fastener holes were drilled through 12x4x0.330" pieces of 7075-T651 aluminum alloy plate. Fatigue cracks were produced in most of these using electro-discharge machining and tensile loading. They were generated such that the propagation direction was normal to the principal tensile stress axis (Figure 1(a)). For a given coupon, the depth of each flaw was controlled such that it was generated either at the bottom of the countersink (CS), at the mid-bore (MB) or at the faying surface (FS) of each hole as shown in Figures 1 (b), (c) and (d), respectively. Several coupons were left unflawed (MS). Eighty-two coupons (58 with cracks and 24 without cracks) were

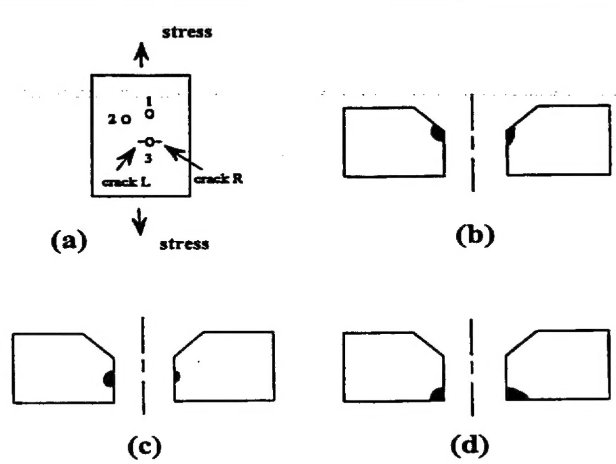


Figure 1 - *Relative position of each type of flaw: ((b)-countersink, (c)-mid-bore, (d)-faying surface).*

manufactured. Production methods and the exact location, size and geometry of each of the defects are described in detail using schematic diagrams in Ref 1.

In addition to unflawed coupons (MS), a total of ten coupons of each type, labelled CS 1 to 10, MB 1 to 10, and FS 1 to 10 was selected. Four specimens of each type were each fastened to 4x4x0.25" aluminum plates using Hi-Lok HL21-8 alloy steel fasteners (0.25x7/8") and HL79-8 aluminum collars. As part of an international testing program, one coupon of each type (with ferrous fasteners) was selected and sent to each of the three other participating countries. The set of remaining specimens was the subject of the current study.

Experimental

Details of the ultrasonic shear wave technique employed during this study have been described elsewhere (2). Briefly, the test specimens were mounted so that the known crack plane was oriented normal to the transducer axis. A 70° angle of incidence ultrasonic shear wave was used and the resulting reflections from the flaws were measured. All data were acquired using commercially-available, immersion C-scan instrumentation (Tektrend International Inc.) and a highly-focussed 25 MHz transducer. Full waveform C-scan data sets for individual holes were obtained by scanning the transducer in a 1" x 1" square raster pattern centered over the fastener. Data for multiple holes were obtained by increasing these dimensions to 2" x 2". A 256 element A-scan, sampled at 8-bit resolution, was acquired at each point of a 256 x 256-element C-scan grid. Four data sets, corresponding to four discrete depths within each coupon were acquired during each scan.

After preliminary experimentation in which parameters such as receiver gain, gatings and offsets were varied, a set of instrument settings was selected and each of the three holes in each of the coupons in the set was scanned under these fixed conditions. Scans were conducted on most of the holes when fasteners were removed as well as with ferrous and titanium fasteners installed. The effect of changing the transducer/crack plane orientation was also examined. Experiments in which all three holes in a coupon were scanned simultaneously were also performed, both with and without fasteners.

Results and Discussion

Ultrasonic images obtained from an unflawed specimen are shown in Figure 2 while Figure 3 shows similar information from a hole with 0.039" and 0.071" cracks on the left and right sides of the countersink (CS07). There was no fastener in either example. Each figure shows (a) the image from the C-scan and (b) an isometric representation of the scan which maps the data points into a projected elevation. Reflections from the outer radius of the countersink hole, the inner bore radius, and the back surface of the countersink are seen as bright areas in each C-scan. The presence of flaws or defects results in additional reflections that are seen as bright spots (or

elevated areas in the isometric images) on either side of the "primary" image in Figure 3.

Changes in the ultrasonic image obtained when a ferrous or a titanium fastener was installed are shown in Figure 4. Three different isometric images are shown, each obtained using the same specimen (CS01, hole 1, 0.006" crack on right side). In Figure 4(a), with no fastener installed, the flaw is clearly seen on the right side of the reflection from the outer radius of the hole. Similar information was obtained when a ferrous fastener was installed, as seen in Figure 4(b), but in this case additional reflections from the edge of the fastener are present and some of the reflections from the back surface of the hole are masked. Because of relatively deep slots in it's head, the presence of a titanium fastener resulted in the more complicated image seen in Figure 4(c). However, the image of the flaw is still evident.

Due to their method of generation, the orientation of the cracks in these coupons was known and most of the ultrasonic scans were made with the transducer axis normal to this direction. A limited number of specimens were examined with the coupons rotated approximately 45° or 90° from this orientation. The different images obtained from the same hole (CS09, hole 2, 0.024" flaw on each side) are shown in Figure 5. The "normal" orientation, Figure 5(a), indicates the presence of flaws of approximately the same size on each side of the fastener hole. When the coupon was rotated 45°, Figure 5(b), the magnitude of the reflections from the flaws was reduced and appear on an oblique axis through the centre of the hole. When the coupon was rotated 90°, Figure 5(c), reflections from the flaw originally on the right side of the hole are hidden by those from the back surface of the countersink while reflections from the flaw originally on the left side are barely visible in the foreground. Thus, the probability of detecting flaws is maximum when the transducer axis is oriented normal to the crack plane.

Although each hole was inspected individually in this study, it was found that most of the flaws could also be detected when all three holes were included in the same scan, as illustrated in Figure 6. The relatively large flaws in this coupon, FS10, are readily evident. Dimensions of the cracks are given in the caption.

Ref 1 indicates that the smallest cracks at each location in this set of coupons existed in coupons CS01, FS01, and MB03. The ultrasonic shear wave technique was able to detect each of these. Figure 4 shows the known 0.006" crack on the right side of the countersink of hole 1 and Figure 7 indicates the presence of 0.017" and 0.016" flaws on the left and right sides of the faying surface of hole 1, coupon FS01. Although not as distinct as the previous examples, Figure 8 indicates the presence of a 0.022" mid-bore flaw on the left side of MB02, hole 1. The fact that a larger 0.033" crack on the right side of this hole was not detected is unexplained. In general, mid-bore flaws less than 0.100" were not seen.

As mentioned above, one coupon of each type (with ferrous fasteners) was selected and sent to other participating countries as part of an international testing program. For reference, the results of scanning the samples assigned to Canada (MS22, CS03, MB08 and FS06) using the current technique are shown in Figures 9-12. Each of the known cracks is clearly seen.

Table 1 contains a summary of all the results obtained in this study. Flaw dimensions (in 0.001") on the left and right sides (LH and RH, respectively) of each of the holes in each test coupon in the set are tabulated. The shaded cells in the table indicate that these cracks were not detected. The superscripts beside the dimensions in each of the other cells indicate that these flaws were detected, the number referring to the gate in which the flaw was most perceptible. All of the flaws located at the countersink and faying surface were readily detected but, with few exceptions, mid-bore flaws less than 0.100" were not seen. Mid-bore cracks larger than this size were identified without difficulty.

Conclusions

The ultrasonic shear wave technique used in this study was readily able to detect a variety of fatigue cracks in different known locations and with known dimensions in countersunk fastener holes drilled through 7075-T651 aluminum alloy plate both with and without fasteners installed. The smallest crack detected was 0.006", although most cracks were greater than 0.010" and some crack dimensions were as large as 0.25". All of the flaws located at the countersink and faying surface were readily detected but, with few exceptions, mid-bore flaws less than 0.100" were not seen.

Although the insertion of ferrous or titanium fasteners changed some features of the ultrasonic images obtained, their presence or absence did not adversely affect the detectabilty of the flaws.

It was found that the ability of this technique to detect cracks successfully is highy dependent on transducer /crack plane orientation.

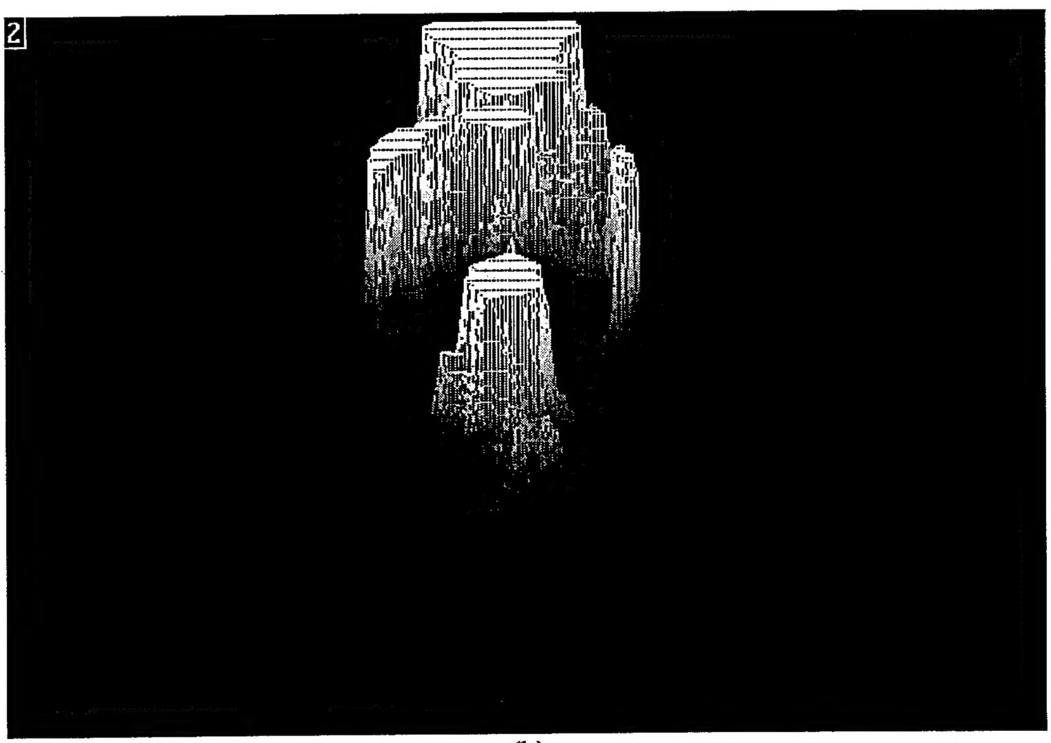
Even though this study demonstrated that this technique is effective in detecting the presence of relatively small cracks under installed fasteners, it is not directly applicable to field use. It is an immersion technique, making it unsuitable for on-aircraft applications. The process also requires 15-20 minutes per scan, making it impractical for inspecting large numbers of holes. It is possible, however, that current on-aircraft scanning capabilities could be modified in order to perform this technique.

References

1. CF116 Upper Wing Skin Golden Triangle POD Specimens, QETE Project Number A013692, December 1993

2. Ultrasonic Imaging of Cracks Under Installed Fasteners, Kenneth I. McRae and Richard W. Nolan, 1st USAF, NASA, FAA Conference on Aging Aircraft, Utah, July 1997

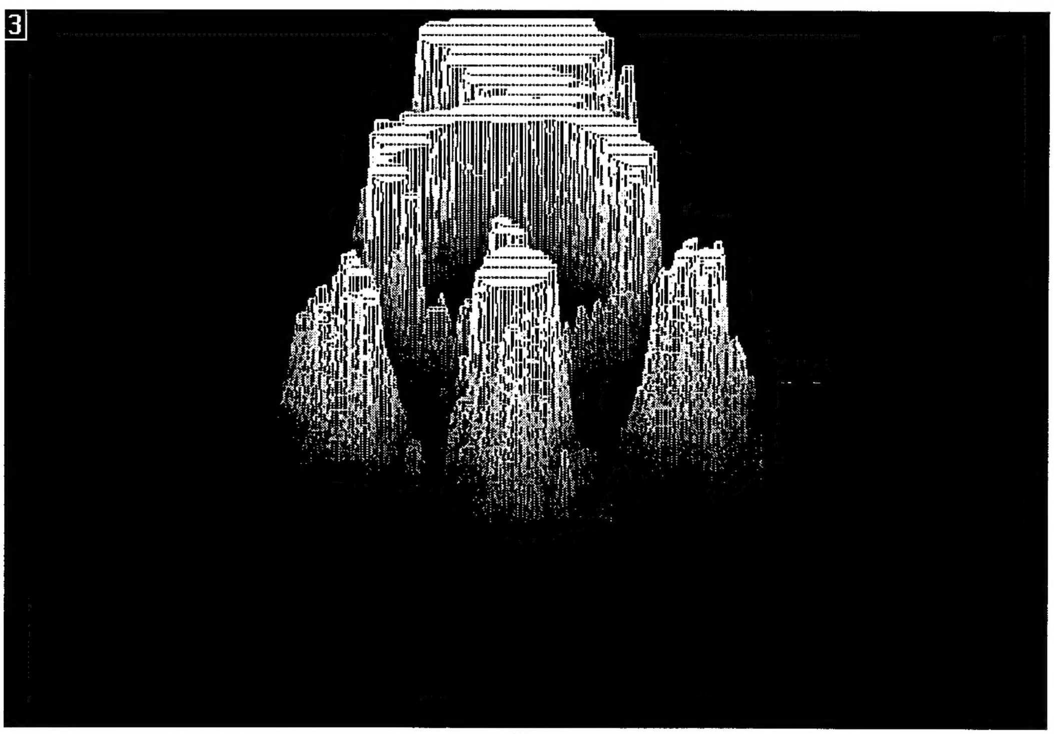
(a)



(b)

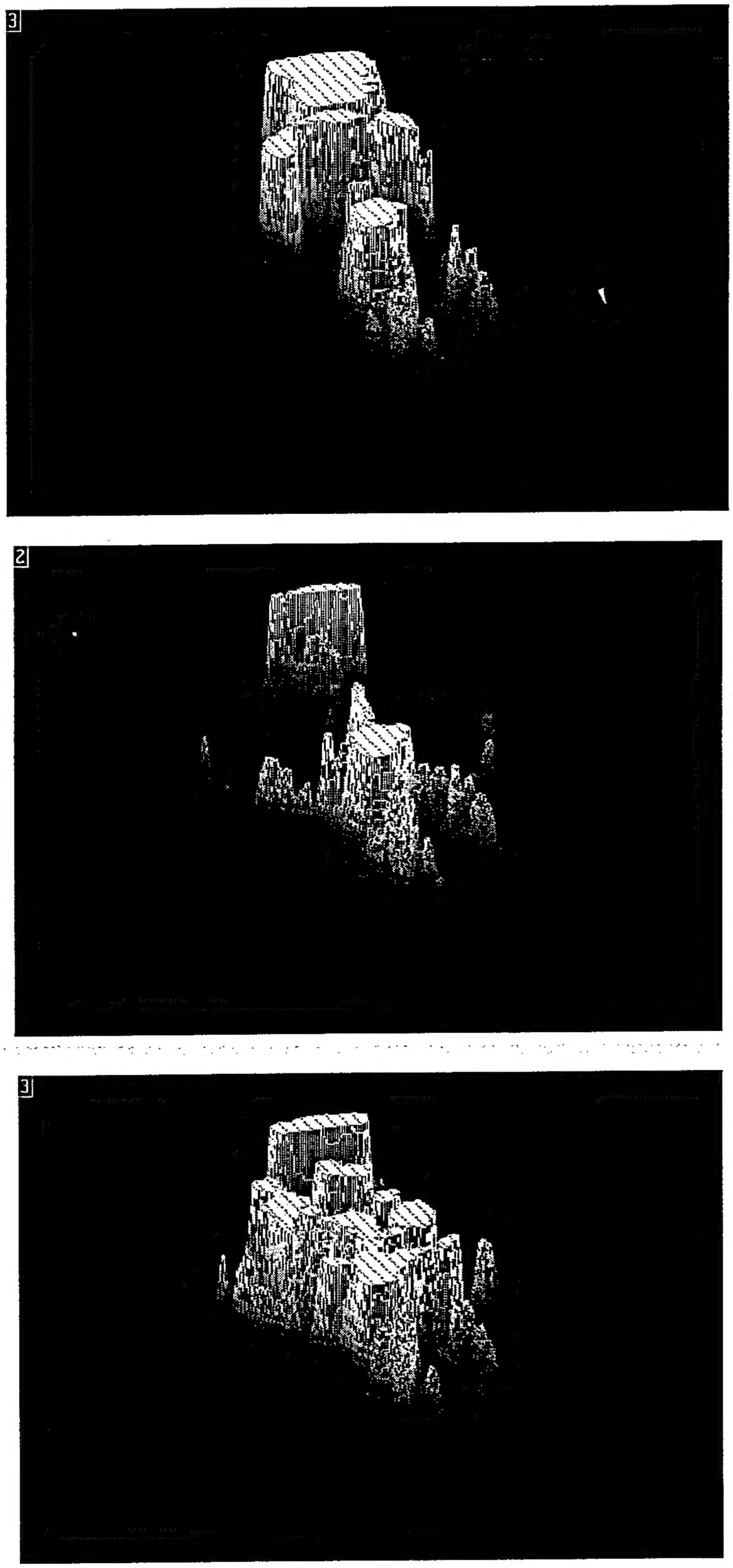
Figure 2 - *Ultrasonic images of unflawed hole. (a) C-scan, (b) isometric projection.*

(a)



(b)

Figure 3 - *Ultrasonic images of flawed hole (CS07, hole 3 (0.039" & 0.071" flaws on left and right sides of bottom of countersink). (a) C-scan, (b) isometric projection.*

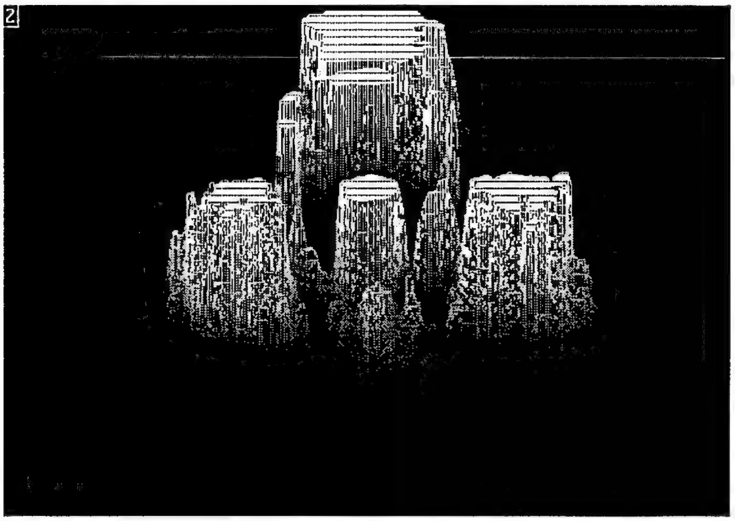


(a) - no fastener

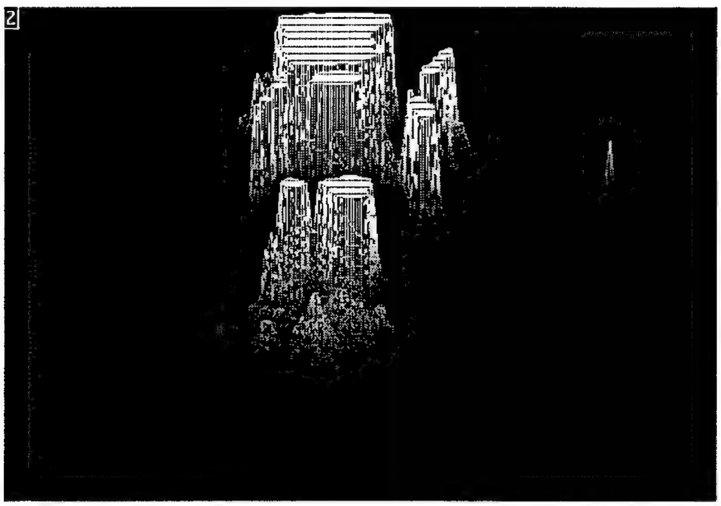
(b) - ferrous fastener

(c) - titanium fastener

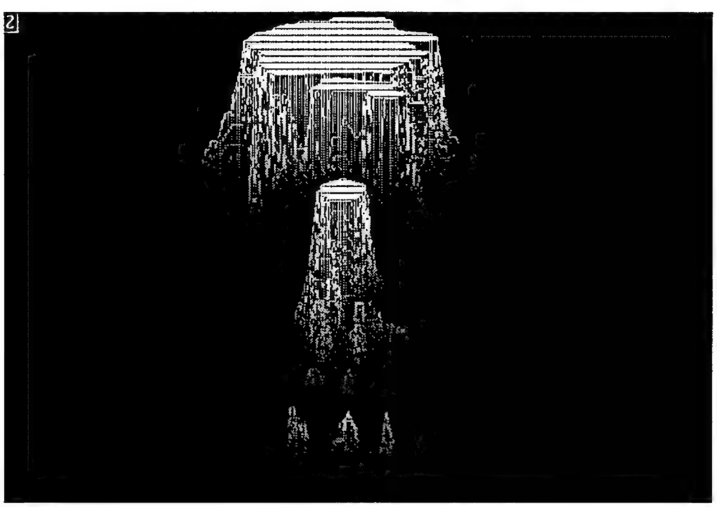
Figure 4 - *Ultrasonic images of CS01, hole 2 (0.006" flaw on right side) with ferrous and titanium fasteners.*



(a) - "normal" orientation

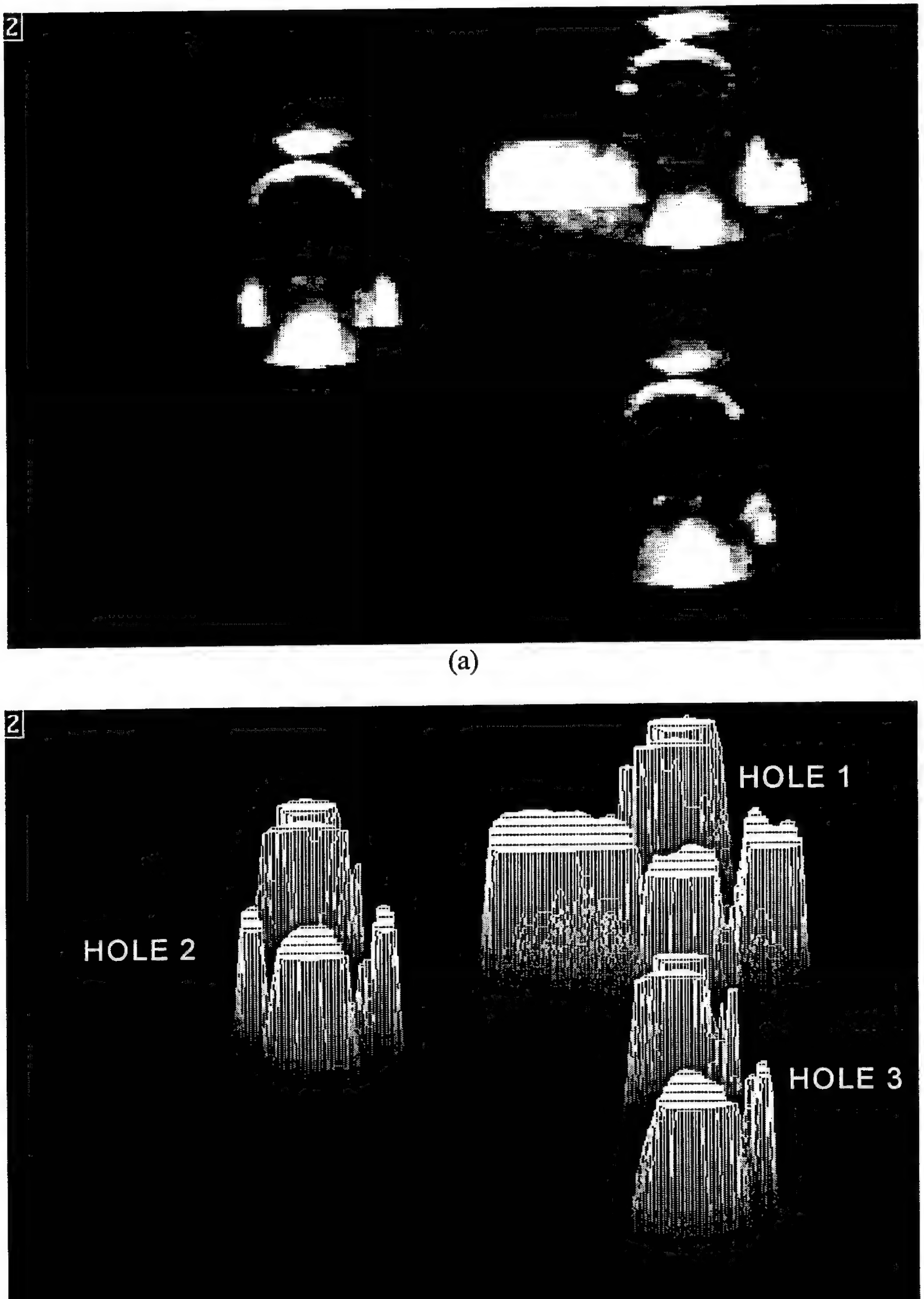


(b) - coupon rotated 45°



(c) - coupon rotated 90°

Figure 5 - *Ultrasonic images of CS09, hole 2 (0.024" flaw on each side) with different transducer/crack plane orientations.*

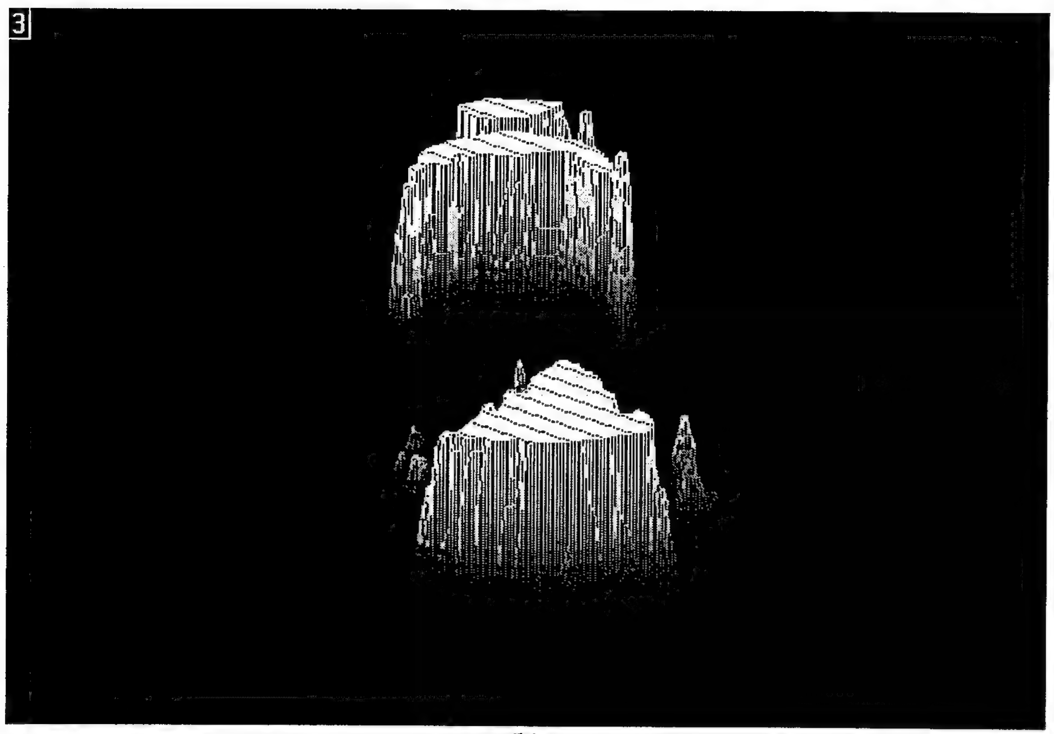


(a)

(b)

Figure 6 - *Ultrasonic images of FS10, holes 1 (0.301",0.110"), 2 (0.050",0.046") 3(0.024",0.020"). (a) C-scan, (b) isometric projection.*

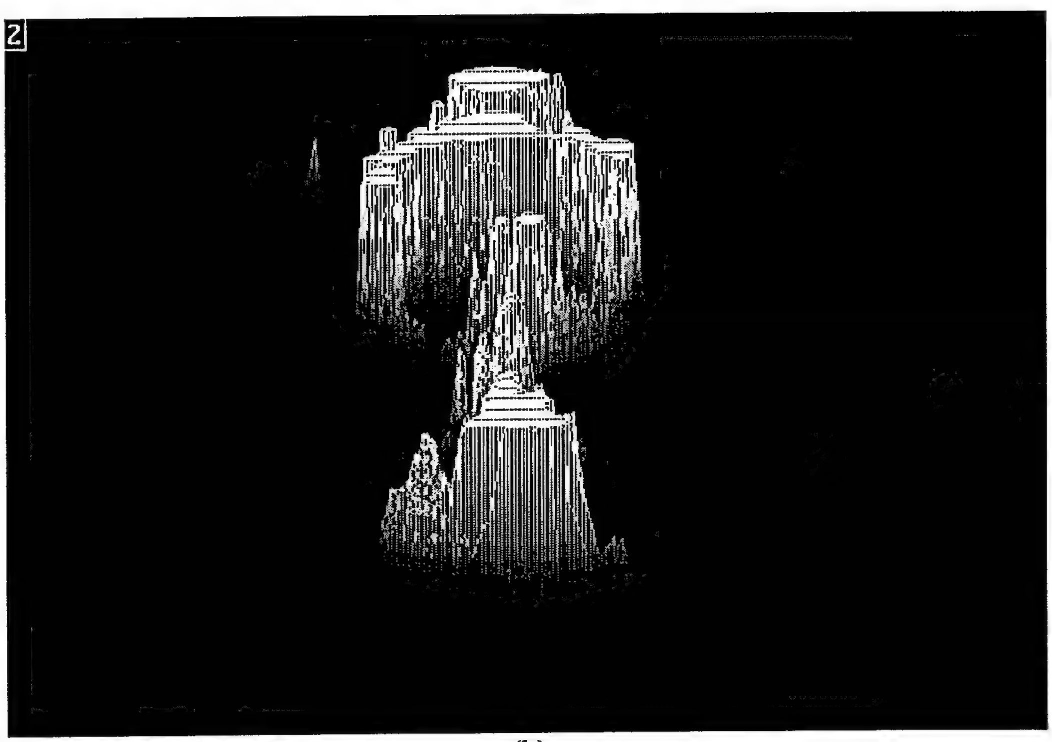
(a)



(b)

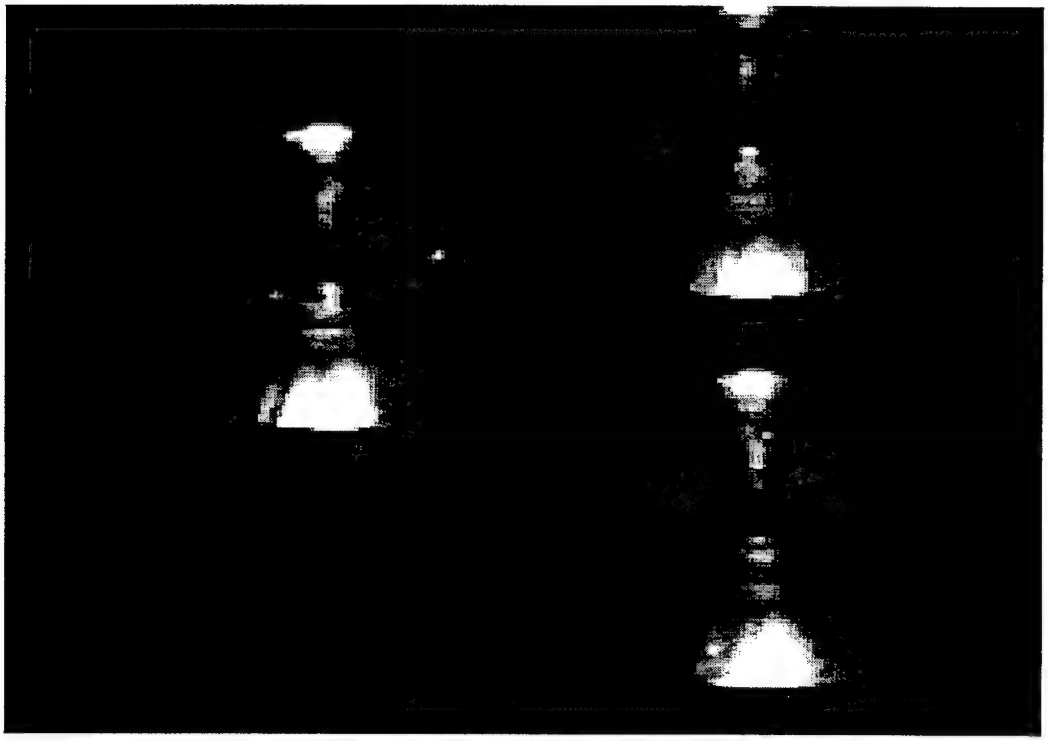
Figure 7 - *Ultrasonic images of FS01, hole 1 (0.017" & 0.016" flaws on left and right sides of faying surface). (a) C-scan, (b) isometric projection.*

(a)

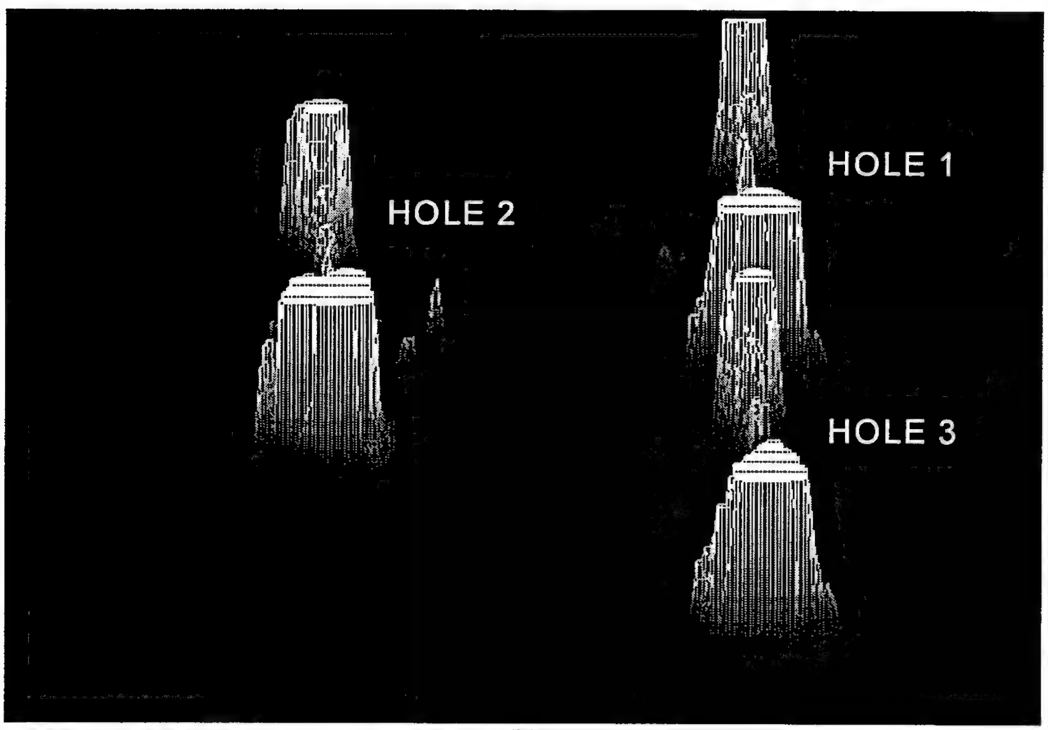


(b)

Figure 8 - *Ultrasonic images of MB02, hole 1 (0.022" & 0.033" flaws on left and right sides of mid-bore). (a) C-scan, (b) isometric projection.*



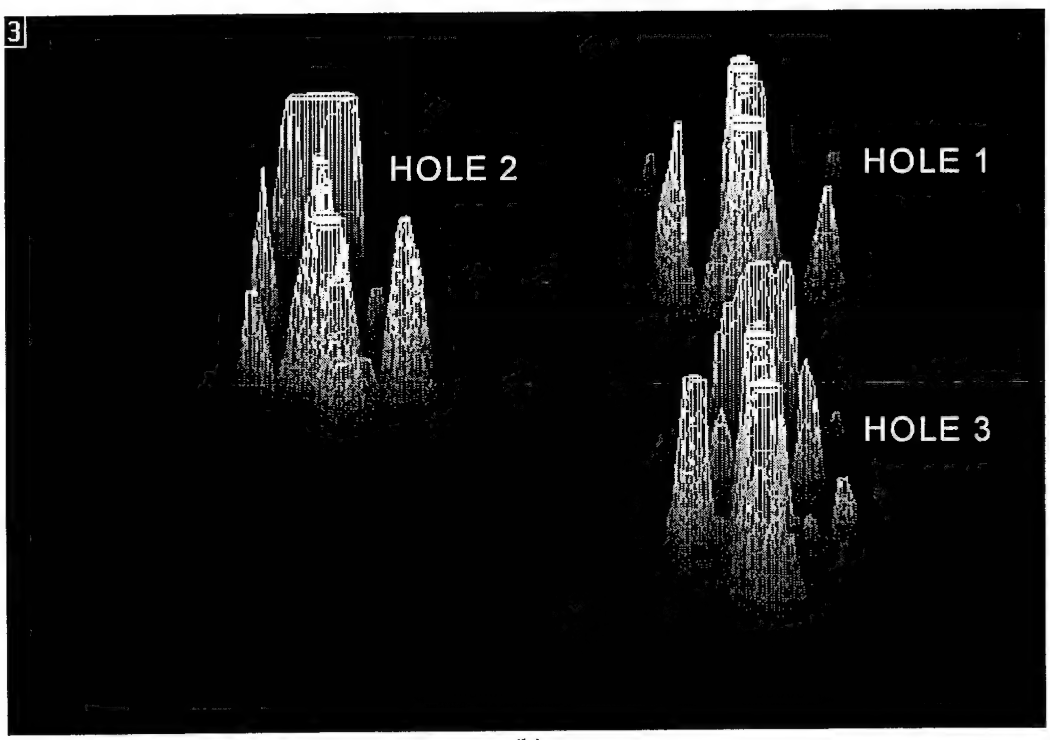
(a)



(b)

Figure 9 - *Ultrasonic images of MS22, holes 1, 2 and 3 (no flaws).*
(a) C -scan, (b) isometric projection.

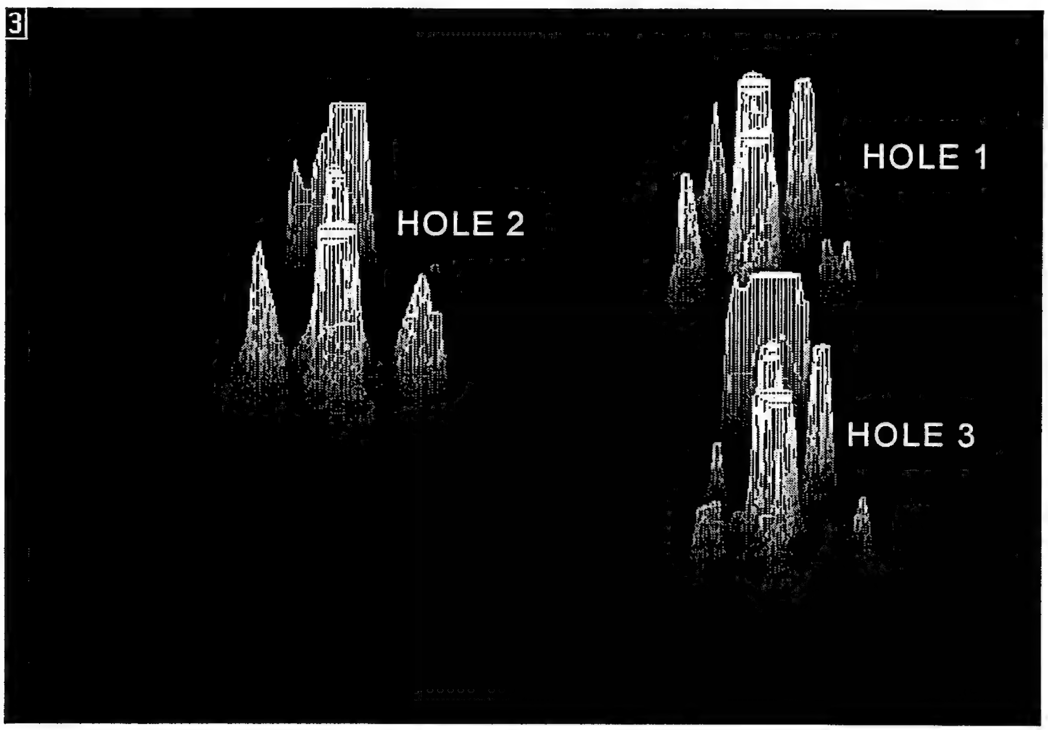
(a)



(b)

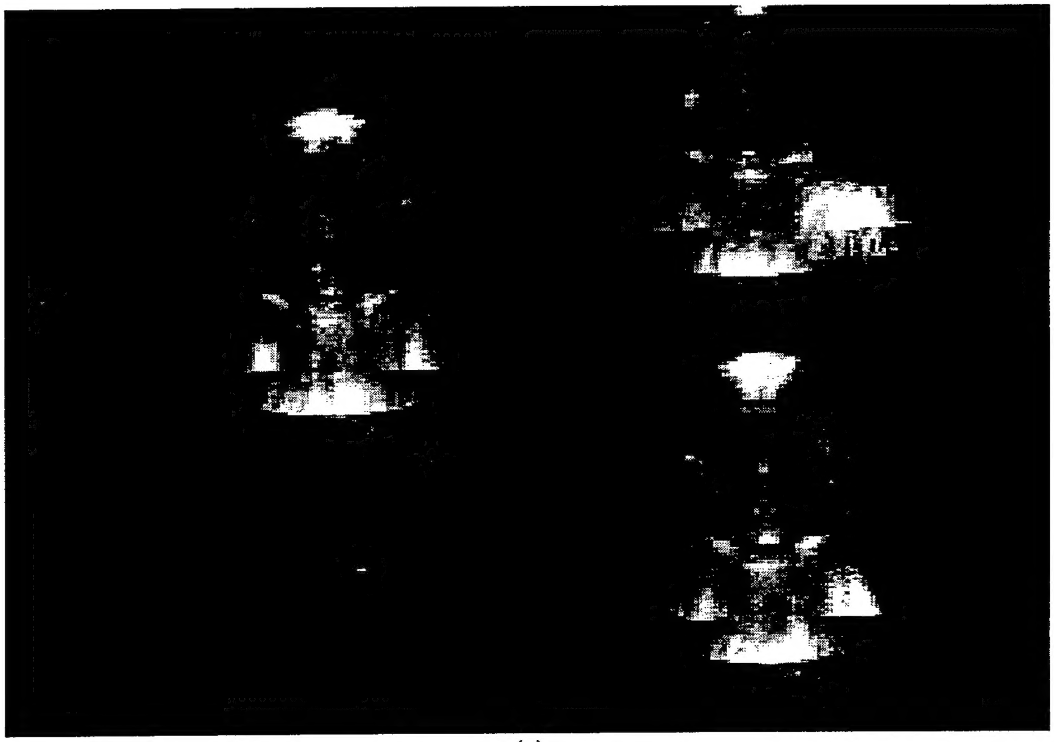
Figure 10 - *Ultrasonic images of CS03, holes 1 (0.043",0.031"), 2 (0.024",0.047") 3(0.030",0.024"). (a) C-scan, (b) isometric projection.*

(a)

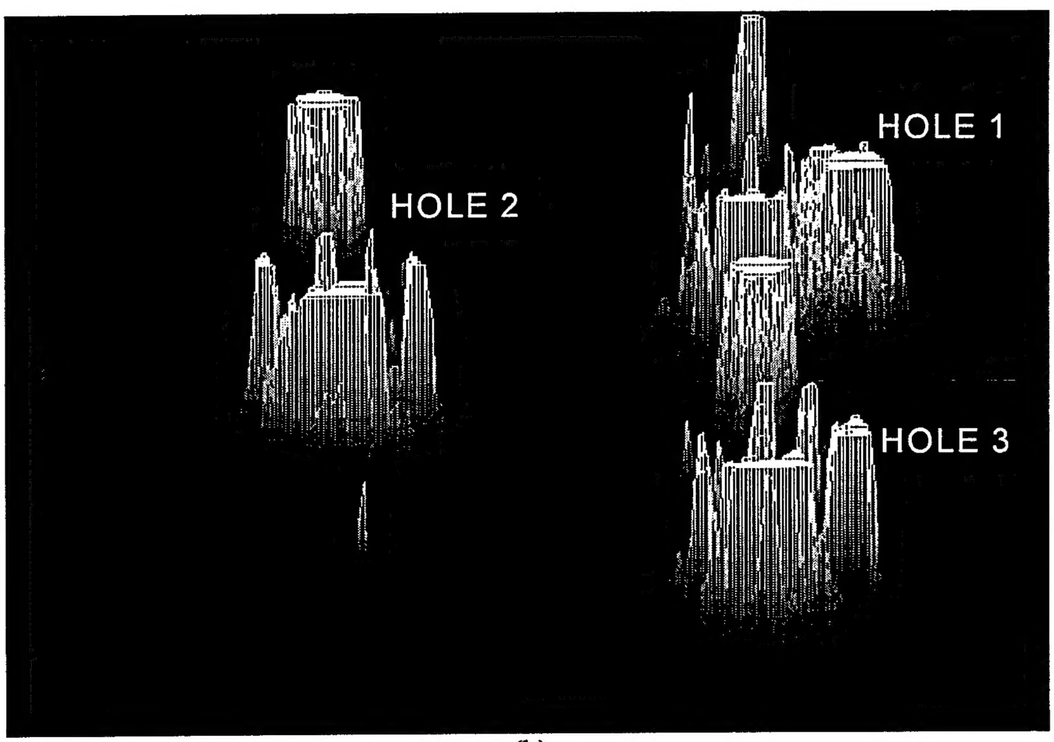


(b)

Figure 11 - *Ultrasonic images of MB08, holes 1 (0.108",0.113"), 2 (0.152",0.181") 3(0.099",0.089"). (a) C-scan, (b) isometric projection.*



(a)



(b)

Figure 12 - *Ultrasonic images of FS06, holes 1 (0.033",0.098"), 2 (0.044",0.048") 3(0.031",0.035"). (a) C-scan, (b) isometric projection.*

Table 1

QETE Test Coupons - Summary of Crack Sizes and Their Detectability
Shading indicates that flaws were not detected. Superscripts indicate gate of optimum visibility. Flaw sizes are in 0.001"

No.	COUNTERSINK						MID - BORE						FAYING SURFACE					
	HOLE 1		HOLE 2		HOLE 3		HOLE 1		HOLE 2		HOLE 3		HOLE 1		HOLE 2		HOLE 3	
	LH	RH	LH	RH	LH	RH	LH	RH	LH	RH	LH	RH	LH	RH	LH	RH	LH	RH
1	nil	nil	nil	$.006^{2}$	nil	nil	.043	.037	.047	.049	$.044^{4}$	.040	$.017^{3}$	$.016^{3}$	$.045^{3}$	$.033^{3}$	$.045^{3}$	$.028^{3}$
2	$.018^{2}$	$.014^{2}$	$.026^{2}$	$.035^{2}$	$.008^{2}$	$.020^{2}$	$.022^{3}$	.033	.055	.044	.041	.024	$.030^{3}$	$.030^{3}$	$.031^{3}$	$.038^{3}$	$.032^{3}$	$.042^{3}$
3	$.043^{2}$	$.031^{2}$	$.024^{2}$	$.047^{2}$	$.030^{2}$	$.024^{2}$	$.042^{4}$	.039	.035	.074	.023	.050						
4							.044	.041	.044	.060	.043	.077						
5																		
6													$.033^{3}$	$.098^{3}$	$.044^{3}$	$.048^{3}$	$.031^{3}$	$.035^{3}$
7	$.079^{2}$	$.075^{2}$	$.106^{1}$	$.110^{1}$	$.039^{2}$	$.071^{2}$							$.016^{3}$	$.048^{3}$	$.098^{3}$	$.112^{3}$	$.036^{3}$	$.059^{3}$
8	$.106^{2}$	$.075^{2}$	$.110^{2}$	$.124^{2}$	$.079^{2}$	$.075^{2}$	$.108^{2}$	$.113^{2}$	$.152^{3}$	$.181^{2}$	$.099^{2}$	$.089^{2}$	$.078^{3}$	$.025^{3}$	$.133^{3}$	$.134^{3}$	$.105^{3}$	$.147^{3}$
9	$.110^{2}$	$.098^{2}$	$.250^{2}$	$.250^{2}$	$.091^{2}$	$.102^{2}$	$.076^{2}$	$.108^{2}$	$.147^{3}$	$.181^{3}$	$.118^{2}$	$.117^{2}$	$.193^{3}$	$.048^{3}$	$.046^{3}$	$.067^{3}$	$.024^{3}$	$.034^{3}$
10							$.200^{3}$	$.225^{3}$	$.225^{3}$	$.225^{3}$	$.180^{4}$	$.200^{4}$	$.301^{3}$	$.110^{3}$	$.050^{3}$	$.046^{3}$	$.024^{3}$	$.020^{3}$

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The detection of fatigue cracks under installed fasteners in aircraft structures has been an area of concern for many years. This paper describes results obtained using a 70° angle of incidence ultrasonic shear wave technique to systematically inspect countersunk fastener holes in aluminum plates with simulated fatigue cracks of known dimensions and locations. Holes were inspected with ferrous and titanium fasteners installed as well as without fasteners.

It was concluded that this technique was readily able to detect a variety of fatigue cracks in holes both with and without fasteners installed. The smallest crack detected was 0.006", although most cracks were greater than 0.010" and some crack dimensions were as large as 0.25".

Although it was shown that this technique was capable of detecting the presence of relatively small cracks, it is not directly applicable to field use. It is an immersion technique and requires 15-20 minutes per scan, making it impractical for inspecting large numbers of holes. It is possible, however, that current on-aircraft scanning capabilities could be modified in order to use this procedure.

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